SECTION 1 - INTRODUCTION

1.1 The UK Marine Aggregate Dredging Industry

Marine aggregate mining in the United Kingdom for construction purposes has averaged 20-28 million tonnes per annum over the past 9 years (*see* Table 1.1) totalling 213.6 million tonnes. In 1995, some 26 million tonnes of sand and gravel was won from marine sources (permitted removal 45 million tonnes), with slightly over 18 million tonnes landed on the south and east coast, including Thames Estuary ports. Total tonnage increased slightly to 26.6 million tonnes in 1996. 12% (3.3 million tonnes) was landed at English Channel ports. Aggregate for fill and beach nourishment purposes varied between 0.8 million tonnes in 1993 to 5.2 million tonnes in 1995 and is likely to form a significant growth area into the next decade. 42 vessels are presently known to be engaged in UK marine aggregate mining. Marine dredged aggregate supplies 18% of England and Wales' total aggregate demand, rising on a regional basis to over 30% of total demand for the South East of England (BMAPA, 1995). The UK industry is second only to Japan, where 85% of all aggregate are supplied from marine sources (Tsurasaki *et al*, 1988, *in* Selby & Ooms, 1996).

UK Government forecasts state that a provision for the supply of 320 million tonnes of marine aggregate should be made over the period 1992-2006 (DoE Minerals Planning Guidance (MPG) Note 6, 1994). This requires maintaining output at over 20 million tonnes per annum. Clearly, a co-ordinated resource management approach including industry, government and the public is required. MPG (6) states; "*There will be a presumption against extraction unless the environmental and coastal impact issues are satisfactorily resolved*". MPG (6) is presently under review, and is expected to be reissued in 1999.

Year	East Coast	Thames Estuary	South Coast	Bristol Channel	Liverpool Bay	Rivers	Fill & Beach Nourishment	TOTAL	% landed abroad
1988	10.0	2.95	5.53	2.96	0.43	0.07	3.86	**25.8**	9.2
	(15.8)	*(6.35)*	*(8.96)*	*(5.00)*	*(2.1)*			***(42.07)***	
1989	10.9	3.6	5.70	2.91	0.47	0.12	4.34	**28.04**	9.0
	(16.8)	*(6.35)*	*(10.87)*	*(4.98)*	*(2.1)*			***(41.1)***	
1990	10.9	2.1	6.19	3.25	0.49	0.10	2.26	**25.29**	15.1
	(16.4)	*(6.35)*	*(13.81)*	*(5.03)*	*(2.1)*			***(46.05)***	
1991	9.22	1.51	5.28	2.07	0.31	0.04	1.93	**20.36**	22.6
	(16.4)	*(6.35)*	*(12.1)*	*(5.19)*	*(1.26)*			***(41.3)***	
1992	10.26	1.5	4.79	2.39	0.31	0.02	1.29	**20.56**	30.7
	(16.4)	*(6.35)*	*(13.55)*	*(5.19)*	*(1.38)*			***(42.87)***	
1993	9.81	1.22	4.36	2.17	0.38	0.01	0.8	**18.75**	33.2
	(16.3)	*(6.35)*	*(10.15)*	*(5.11)*	*(0.7)*			***(38.61)***	
1994	11.29	2.0	4.93	2.26	0.29	0.02	1.29	**22.08**	30.1
	(16.0)	*(6.35)*	*(9.74)*	*(4.81)*	*(0.81)*			***(37.74)***	
1995	12.3	1.66	4.43	2.29	0.28	0.01	5.17	**26.14**	26.1
	(16.0)	*(6.85)*	*(13.55)*	*(4.84)*	*(0.80)*			***(42.04)***	
1996	11.21	1.12	4.74	2.02	0.29	0.02	7.22	**26.62**	25.1
	(18.5)	*(6.65)*	*(13.25)*	*(4.62)*	*(0.68)*			***(43.7)***	
Mean	**10.65**	**1.96**	**5.11**	**2.48**	**0.36**	**0.05**	**3.13**	23.74	**22.3**
	(16.5)	***(6.44)***	***(11.78)***	***(4.97)***	***(1.33)***			*(41.72)*	

Table 1.1 *Summary statistics of the United Kingdom marine aggregate dredging industry. Figures show tonnage (million tonnes per annum) actually removed compared with maximum permitted removal (italics in brackets) on a regional basis. Tonnage landed abroad calculated as percentage of total dredged (modified from: The Crown Estate 1989-1997)*

Without doubt there is an increasing awareness of the full range and importance of the environmental issues of relevance to the marine aggregate mining industry. Latterly, however, there has been a growing collection of alleged and largely unsubstantiated concerns, in particular over the potential impact of the generated plume on seabed fisheries resources, but also of aggregate dredging operations in general.

By the very presence of a draghead acting upon the seabed during a dredging operation, changes in the physical environment will be observed within and, to a certain extent, beyond the dredged area. Generally, these are considered of a short term nature, such as the resuspension and subsequent settlement of sediments or medium term, such as the temporary removal of benthos and subsequent recolonisation. Any removed fractions may or may not be replaced by naturally occurring, omnipresent sea bed processes over the longer term. Semi-permanent changes such as removal of coarse sediments may also be considered, whereby the removed sediment fractions are unlikely to be replaced by similar material during present day (geological sense) naturally occurring seabed processes.

'Impacts' of dredging may further be considered in terms of spatial effects, where most of these will be localised in nature, for example, changes in bottom topography. The spatial impact of plumes, however, may extend beyond the boundary of the dredged area, and in combination with the easily identified visual surface expression, has thus attracted much recent attention for investigation and monitoring. Any impact determined to be due to the formation of a plume and its associated effects must however be put into perspective and considered in association with all other aspects of the dredging operation, a process undertaken during the preparation of the Environmental Assessment (EA).

The Environmental Assessment must determine the relative importance of plume and turbidity generation and will necessarily require assessment of each dredging scenario within its proposed environment, fully taking into account natural and artificial variables. Not only is an understanding of plume generation and dynamics therefore required but also knowledge of baseline conditions, natural environmental variability and responses to disturbances in the vicinity of the dredged areas.

The environmental significance of sediment plumes and other forms of disturbances which are inevitably generated by all forms of dredging operations has long been recognised (*see, for example*, Taylor & Saloman, 1968; Kaplan, 1974; Oulasvirta *et al*, 1978; Saloman *et al*, 1982, also Pagliai *et al* 1985; Borst *et al*, 1994; Morton, 1996). In conjunction with dredging of cohesive sediments (principally maintenance dredging but also capital dredging) and deep ocean minerals mining (*for example see* Lavelle *et al*, 1981), a number of studies have investigated the sources of plumes, their mechanisms of advection, dispersion and sedimentation, and their physical and biological effects (*see, for example*, Böhlen, 1978 & 1980; Kojima, 1986; Madany, 1987; Oulasvirta *et al*, 1988; Åker *et al*, 1990; Nielsen *et* al, 1991; Burnett & Whiteside, 1992; Drapeau *et al*, 1992; Vitanen, 1993; Thevenot & Johnson, 1994; Tubman *et al*, 1994; Pennekamp *et al*, 1996).

The information available specifically for marine aggregate mining is less widespread. The International Council for the Exploration of the Sea (ICES) maintains an annual review of the impacts of marine dredging for aggregate (*see, for example*, ICES, 1992a; 1992b; 1993; 1994; 1995; 1996). Reviews of aspects of sand and gravel extraction practices overseas and impacts thereof include van der Veer *et al* (1985), de Groot (1986), Hurme & Pullen (1988), Charlier & Charlier (1992) and Hammer *et al,* (1993). Recently the impacts of specific forms of marine mining including precious metals, marine aggregate and heavy mineral sands have been assessed in a detailed study for the United States, Department of the Interior, Minerals Management Service (MMS) (C-CORE, 1996).

The results of few environmental impact studies have filtered through into the scientific community, principally through the medium of ICES (*see, for example*, Sips & Waardenburg, 1989; van Moorsel & Waardenburg, 1990 & 1991; de Jong & van Moorsel, 1992; van Moorsel, 1993 & 1994). However, many environmental studies and impact assessments have been commissioned by industrial sponsors (including the marine aggregate industry) in recent years but these largely remain '*Commercial In Confidence'* or within the '*grey literature*' of non-refereed, technical reports with little circulation amongst the wider scientific community.

Our review of the literature indicates there is little information available relating to detailed investigations of plumes *per se* in UK waters; these have largely been undertaken abroad. Impacts and descriptions of the generated plume have been reported elsewhere (*see* Willoughby & Crabb, 1983; Poiner & Kennedy, 1984; Clarke *et al*, 1990; Foster *et al*, 1991). More recently , a number of authors have dealt with the dynamics of the plume generation and behaviour (Land *et al*, 1994; Bonetto, 1995; Jensen *et al*, 1995; Weiergang, 1995; Whiteside *et al*, 1995; Paris & Martinez, 1996).

Information specifically generated for aspects of the UK industry is more scarce. Reviews of the UK marine aggregate dredging industry have been prepared by Nunny & Chillingworth (1986); Drinnan & Bliss (1986); Pasho (1986) although the latter two were commissioned for overseas interests. Further information appears sporadically in the ICES literature. Gross impacts associated with marine aggregate extraction on local biological communities have been assessed by Shelton & Rolfe (1972); Millner *et al* (1977); Rees (1987); Lees *et al*, (1990); Kenny *et al*, (1991). Biological and geological conditions and responses to disturbance have been reported by Dickson *et al* (1979); Kenny & Rees (1994; 1996). Physical observations of the impacts of dredging were made by Dickson & Lee (1973) and Price *et al* (1978) with little further work appearing until Davies & Hitchcock (1992). Observations of the physical behaviour of plumes appears limited to that which has been reported largely since the inception of the this project (*see, for example*, Marsh, 1994; Hitchcock & Drucker, 1996; Dearnaley *et al*, 1996). It is known that other studies are in progress, particularly some recently funded by MAFF, from which results are expected shortly.

Mitigation tools such as silt screens, silt curtains and anti-turbidity overflow systems (Ofuji & Ishimatsu, 1976; Nakata *et al*, 1989; Horii, 1996) have been reported overseas, although many European technological improvements may exist as internal reports and under restrictions of patent.

1.2 Project Background & Purpose

Interest in the potential of marine aggregate mining from the United States Federal Outer Continental Shelf (OCS) as a source for beach recharge and barrier island protection material has grown rapidly in recent years as State resources of such material (predominantly within three miles of the coastline) have become depleted and/or polluted. The suitability of these deposits for construction purposes is also being examined. Additionally, increasing concern over potential deleterious coastal effects as a direct or indirect consequence of nearshore dredging activities has resulted in increased interest in the reality of offshore exploitation. Federal waters will largely be beyond the limit of regular seabed interaction by predominant wavebase conditions and only remotely connected to onshore/offshore processes.

The Office of International Activities and Marine Minerals (INTERMAR) of the Minerals Management Service (MMS), a Bureau within the United States Department of the Interior, has clear responsibilities for providing environmental analysis and assessment information facilitating the responsible management of these resources. This project was formulated to encompass several key elements of interest to INTERMAR and the MMS's Marine Minerals Programme. Principally, the requirements for information regarding the origin and dynamics of benthic and surface sediment plumes, previously identified in several INTERMAR and State/Federal Task Force documents, are addressed by this project.

In the United Kingdom, the Department of the Environment (DoE) adopted document *Guidance On Environmental Assessment for Marine Aggregate Dredging Proposals* as prepared by the ICES Marine Environmental Quality Committee Working Group (ICES, 1993) has become a *proforma* by which environmental assessments in the U.K. for marine aggregate extraction are prepared. This document has been incorporated within the U.K. Ministry of Agriculture, Fisheries and Food *(MAFF)* Directorate of Fisheries Research (DFR) Laboratory Leaflet No. 73 *Guidelines for assessing marine aggregate extraction* (Campbell, 1993). Summarising a central objective of this project, Items 1.2.1vi & vii (Campbell, 1993) require detailed consideration of:

- *vi transport and settlement of fine outwash sediment suspended by the dredging activity or from an outwash plume;*
- *vii effects of onboard screening/grading*

Complementing the DoE guidelines, the scoping document prepared by the International Council for the Exploration of the Sea *(ICES)* Marine Environmental Quality Committee (ICES, MEQC 1993) highlights the need for establishing data on;

- (2a) ... *stability, mobility and turbidity of bottom sediments and natural suspended loads*

- (3a) ... *information on predicted transport and settlement of fines suspended by the dredging activity, from an outwash plume or from onboard screening/grading*

This study is timely for contribution to the competent production of environmental statements and assessments as existing and developing legislation dictates at both national and international levels. The environmental information is relevant to dredging operations for sand and/or gravel on the U.S. continental shelf, either during the preparation of environmental impact statements, or during review of marine mineral development plans.

Further, the study results may be interpreted to indicate technological areas in which operational efficiency may be increased, mitigating some environmental consequences of the operations and assisting development of an environmentally responsible offshore industry.

1.3 Project Approach & Objectives

Recognising the technological, environmental and legislative management practices forged during the successful development of the United Kingdom marine aggregate industry, the MMS initiated interagency discussions with responsible parties in the U.K. Information gathered resulted in the MMS acting as prime funding agency for this project to provide important environmental data to advance their developing legislation and management structures.

Coastline Surveys Ltd has a respected and broadening track record in marine minerals' resource prospecting, environmental monitoring and dredging research and provided in-depth expertise to undertake this work.

The growing status of environmental investigations in the U.K. and the catalytic effect of funding provided by MMS, encouraged and supported Coastline Surveys Ltd (CSL) in securing active participation by the key major U.K. aggregate dredging companies (ARC Marine Ltd, South Coast Shipping Company Ltd and United Marine Dredging Ltd) and the coastal studies' research facility of HR Wallingford Ltd, Ports & Harbours Division. Specialist consultants Marine Ecological Surveys Ltd partnered CSL for preparation of the benthic ecology literature review.

Participation in this project has enabled all project partners to gather hitherto unavailable data on the content and behaviour of sediment plumes developed during normal marine aggregate mining activities both at the sea surface, in mid-water and near the seabed. The U.K. dredging industry has been able to provide valuable seatime aboard a variety of working dredgers on numerous occasions. Importantly a representative sample of the main stream industry working under normal commercial conditions has been investigated.

The objectives of this study may be summarised;

- *to acquire and define source term data on the content of benthic plumes*
- *to acquire and define source term data on overboard plumes*
- *to investigate likely sediment excursion and settling depths*
- *to appraise the changes in seabed character in mind of implications for continued dredging and environmental impact*
- *to appraise technological implications of the study findings*

Requirements by the U.K. industrial partners for several site specific environmental studies arose during the progress of the project. These were encompassed into the project on a collaborative basis, with industry providing additional finance largely to cover charter of coastal survey vessels and MMS extending further use of the U.S. Government survey equipment. The results of these studies are incorporated within this review.

Readers of this Report are reminded that the examination of plumes forms only part of the full Environmental Assessment procedure. Whilst we have treated the subject of plumes in some detail, plumes should rarely play the most significant role in the Environmental Assessment.

1.4 Project Methodology

This project has concentrated on obtaining detailed and comprehensive field measurements of plume dynamics and environmental parameters to understand the significance of the developed plumes. The definition of the fundamental source terms of plumes and observation of their subsequent behaviour in the field has allowed significant revisions to traditional modelling scenarios (*see, for example,* HR Wallingford, 1996).

It is important to clarify that this project is concerned with characterising the generation, behaviour and decay of sediment plumes generated by marine aggregate dredging in shallow (less than 40m) coastal waters within 100km of the coastline. We are not concerned with review of all physical disturbances caused by the operations *per se*, nor with the impacts of capital and maintenance dredging of cohesive deposits. Plume characteristics and impacts associated with the dredging of cohesive deposits will be similar in principle but wider ranging due to greater advection and dispersion, and the important role of contaminants bound to the clay fractions.

The zone of significant impact surrounding a dredging operation has been observed in the field to be far less than modelling exercises have historically suggested. The approach adopted within this project provides key baseline data for refining analytical and mathematical predictive studies. It has become apparent during the conduct of the project that the significant number of parameters involved in the development of plumes and the significance of any subsequent impact is not only very complex, but also largely site specific. Whilst modelling provides the useful "what if?" scenarios at the planning stage, it is not considered a replacement for undertaking field monitoring exercises. Executed competently, and combining physical and biological parameterisation, such field campaigns need not be more expensive than detailed modelling itself.

In order to refine prediction of the likely excursion of a plume, key factors that define the 'source terms' have been investigated. The rate *(kg/s)* and total quantity (t) of overboard discharge of sediment via overspill and screening is fundamentally important. These will vary according to the operating characteristics of the vessel, environmental parameters and the nature of the seabed material. Sediment characteristics of the material returned overboard, *e.g.* particle size distribution and total mass, are required. Parameters on the dynamics of the receiving water body including water depth, wave motions, current strength, duration and direction are required not only for detailed modelling of predicted plume behaviour but also for comparing results between different monitoring campaigns.

The project has committed to integrating modern and traditional monitoring techniques and equipment. Central to the project has been the application of the innovative and technologically advanced R.D. Instruments' BroadBand Acoustic Doppler Current Profiler (ADCP^{TM}). This has enabled accurate monitoring of the plumes formed during the dredging operation, and subsequent high confidence in the location of samples representing the suspended solids maxima and minima, through use of the 'acoustic backscatter' function. This approach enables levels of accuracy of data not economically possible to obtain using a spread of conventional instrumentation.

Combination of accurate field observations with the traditional modelling scenarios has resulted in modifications to the theory of behaviour of the developed plume directly (*see, for example,* HR Wallingford, 1996) and following similar results elsewhere (*see, for example*, Land *et al*, 1995; Weiergang 1995; Jensen, 1995; Whiteside *et al*, 1995; Pennekamp *et al*, 1996). These further concluded that the traditional predictive techniques have overestimated the diffusive ability of the dredge plume.

1.5 Report Structure

This Final Report principally contains the results of field investigations characterising the plume of sediments suspended by aggregate dredging activities. The report has been prepared following completion of all the major objectives set out during the original project proposal. It follows a no-cost extension to the project funding by MMS and the Research Group to allow a complete review of data collected early in 1997, delayed by poor weather conditions from late 1996. During 1998 further important information has been gathered investigating the magnitude of organic loading of the water column during dredging operations. Further spillway samples were also obtained which support the results reported herein.

This Final Report is now made available to the project sponsors taking into account the constructive and supportive responses received to the draft report.

Section 2 presents a comprehensive literature review to consider the source, transport and fate of the suspended material. Examples are drawn from the aggregate industry world-wide. A brief overview of the predictive modelling practices that are used in UK for many of the aggregate Licence applications is given.

Section 3 reviews the methods of monitoring plumes that have historically been developed for monitoring dredging of principally cohesive sediments and which are applicable to aggregate dredging activities. A full description of the techniques developed within this project for field evaluation of sediment plume behaviour is given. This includes principles and practical application of Doppler profiling techniques, herein termed *Continuous Backscatter Profiling* (CBP).

Section 4 reports the field phases of the project that have been completed during this project. Detailed explanation of the measurements of the source terms of sediment plumes are presented. The results for the monitoring of plumes generated by various dredging plant and loading differing cargoes under normal working conditions are reported. The transport rates and sedimentation zones are analysed. Investigation into the magnitude of the hitherto unstudied benthic plume arising from the action of the draghead on the seabed is described. Finally in Section 4.4 we present a hypothesis for the far field component of the surface plume.

Section 5 reviews results of selected pertinent parallel studies, many of which have only lately been concluded. These have been conducted overseas independently. The results from all studies generally conform within the range of expected variation.

Section 6 addresses the complex interactions between the benthic ecology and dredging activity and is reported following an extensive and thorough literature survey. Recommendations are made for supplementing the paucity of information that exists for assessing the benthic response of communities to disturbances, especially for UK waters.

Section 7 identifies outstanding scientific requirements which merit further study to complement this Report and others recently produced. These recommendations are not presented in any specific order of importance, but it is considered that most objectives can be realised within 12-18 months of this report date, answering many current questions.

Conclusions remarks and recommendations are presented in Section 8.